Copy No. 23

ARMAMENT DESIGN ESTABLISHMENT

MINISTRY OF SUPPLY

THE DEVELOPMENT OF AN ANTI-AIRCRAFT ENGAGEMENT SIMULATOR

K. J. RADFORD

ARMAMENT DÉSIGN ESTABLISHMENT

TECHNICAL REPORT

No. 9/53

THE DEVELOPMENT OF AN ANTI-AIRCRAFT ENGAGEMENT SIMULATOR

K. J. Radford

Recommended for publication — h. Simmons
N. Simmons, C.T.2.

Approved for publication — A. P. Wickens.
A. P. Wickens, C.E.A.D.

Abstract:

An anti-aircraft engagement simulator now being used in the A.D.E. is described in detail and its method of use explained. Available details are also given of two improved versions of this simulator which are being made by private firms for use in the A.D.E. The first of these will employ the same basic principles as the model now in use. In the second, however, the necessary measurements and some of the setting-up will be done automatically, thereby saving a considerable amount of operator time.

Armament Design Establishment,
Ministry of Supply,
Fort Halstead,
Nr. Sevenoaks, Kent.
Phone: Sevenoaks 5211.

November, 1953.

1. Introduction

In studies of the effectiveness of fragmenting anti-aircraft projectiles against aircraft targets, the destructive power of the fragments from a projectile is matched against the resistance of the aircraft components to damage, and a calculation is made of the probability that the target is defeated, taking into account the combinations of components which must be damaged in order to bring about this end. It is fundamental to this work that the following should be known for any relative position of projectile burst point and target:

(a) Which components of the target are struck by fragments.

(b) How many fragment strikes are to be expected on any component or, equally well, what solid angle does the component or that portion of the component within the fragment beam subtend at the point of burst.

(c) At what distance is the burst from each of the components struck.

The accurate determination of this information by theoretical methods involves considerable computation. Attempts have been made, notably in References 1, 2 and 3, to put forward methods of calculation of weapon effectiveness in which the use of approximations overcomes the necessity for accurate determination of the above information. Whereas these methods provide a useful means of calculation within the limitations of the approximations, these approximations are demonstrably untrue if the linear dimensions of the components and their distances from the centre of the aircraft are of the same order as the burst distance of the projectile. These conditions arise in particular in assessments involving multi-component aircraft and the larger components, such as the structure or the fuel tanks.

As the problem of determining the solid angle subtended by such a component of irregular shape by theoretical means is most forbidding, recourse has been made to direct measurement at model scale, and an experimental simulator has been built for this purpose. This Mark 1 simulator is necessarily crude and does not incorporate all desirable features, but it has none the less operated for the past eighteen months and much useful work has been done. After experience had been gained in operation of the Mark 1, a specification for a Mark 2 simulator was issued and the apparatus is now nearing completion. This simulator differs from the first in that engineering design has been improved and accuracy is correspondingly greater. Two major and several minor modifications have been made to the method of operation. At the same time as the specification for the Mark 2 was written, a research contract was placed to investigate the use of automatic methods in conjunction with simulators; as a result a Mark 3 model, in which operator time is cut to a minimum and automatic recording of data is employed, is likely to be available in June, 1954.

The general theory concerning the representation of the anti-aircraft engagement at model scale applies to all versions of the simulator and will therefore be given before detailed descriptions of the various versions. Illustrations will however be taken from the existing Mark 1 model in order that the developments in design of the later simulators will appear in the proper chronological order. The three Marks of a simulator are described in detail in Appendices A, B and C and an account of some of the work done to date is given in References 4 and 6.

2. General Description of the Simulator

2.1 The simulator consists, in essence, of an optical source which emits light to represent the beam of fragments from a bursting projectile, and a model target aircraft in which the various components vulnerable to fragments are shown. The parts of the target struck by fragments are taken to be those which are illuminated by the light source. The term "fragment" is used here in its widest sense and includes any type of inert fragment, or any sub-projectile specially designed to attack particular components of the target.

In order to define the relative position of the point of burst with respect to the centre point of the target (defined as a point on the axis of the fuselage selected as convenient) a coordinate system is used with the centre point of the target as origin.

In the Mark 1 simulator a Cartesian system is employed, with the x and z axes horizontal and the y axis vertical; the relative position of the missile burst to the target is set up by moving the target in the x and z directions and the light source in the y direction. A cylindrical polar system is employed in the Mark 2 and is envisaged for the Mark 3 simulator, in order that cylindrical polar coordinates of burst points obtained in the A.D.E. fuse burst pattern simulator* may be transferred without conversion. The z axis in this system is vertical in both the Mark 2 and the Mark 3 models.

The z axis is taken to represent a fixed direction in the engagement under consideration, as convenient to the work in hand. The choice of this fixed direction has in the past rested between the direction of the relative velocity between missile and target and that of the central trajectory (the line through the target centre parallel to the course of the missile).

It is essential that the target course be shown in its correct orientation with respect to the z axis; the details of this setting and the description of the system of coordinates, of angles, and of their relation to other systems in common use, is given in paragraph 3.

Model aircraft are used each consisting of a wire framework into which are fitted models of the vulnerable components and of those portions of the target likely to shield these components. In certain cases, when the complete structure of the target is regarded as vulnerable, solid models are used. The detailed construction of the aircraft varies in the three simulators and is described in later paragraphs.

The majority of fragments from a bursting projectile are thrown out in a volume enclosed by the surfaces of two cones, the common axis of the cones being the axis of the missile. It is the function of the optical head to simulate this beam of fragments by light emitted from a point source, bounded in such a way as to give the correct beam width and orientation. For simplicity of operation at the outset, the assumption is usually made that the density of fragments within the beam is constant. However, in particular cases a varying density can be introduced into any problem by splitting up the beam into small elements, to be considered separately, such that the density over anyone element may be considered uniform.

The optical head can be set up to show either the beam of fragments from a static missile or the "dynamic" beam from the missile in flight. Since the fragments from the missile take a finite time to reach the target, and since in that time the target moves along its direction of flight, a fragment which hits a component does not travel along the line joining the burst point and the position of the component at the time of burst. It travels instead, along a line whose direction depends upon the ratio of the fragment velocity to the target speed. Target travel must therefore be allowed for in determining the components of the aircraft which are struck by fragments; this is done by setting the "dynamic" beam on the optical head and moving the target along its direction of flight by an appropriate amount. This operation and two alternative, but less favoured, methods of simulating

* See A.D.E. V.T. Fuse Technical Note No. 32.

the effect of target travel during fragment flight are described in detail later in the text (para 4.2).

When all adjustments have been made, the information required as listed in para 1 may be obtained by direct measurement.

3. Description of the Coordinate Systems Used

3.1 Position of burst relative to the target centre

The following system of rectangular Cartesian coordinates is used in the Mark 1 simulator to define the burst position of the missile, relative to the target:

Origin: the target centre, i.e. a point on the fuselage axis chosen arbitrarily as convenient

z axis: a convenient fixed direction in the engagement under consideration. This is usually taken to be either the direction of the relative velocity of missile and target or the central trajectory. These directions are, of course, the same in the case of direct ahead or astern attacks. The z axis is horizontal in the Mark 1 simulator.

y axis: a line perpendicular to the z axis, and vertical in the Mark 1 simulator.

x axis: the line perpendicular to the two axes defined above, and with the positive direction appropriate to a right-handed system of axes. It is horizontal in the simulator.

For the Mark 2 simulator, cylindrical polar coordinates have been chosen in order that burst positions may be transferred direct from the A.D.E. fuse burst pattern simulator, as follows:

z axis: as in the Mark 1 Cartesian system. The z axis is vertical in the Mark 2 simulator.

r and ϕ in the plane perpendicular to the z axis.

The same cylindrical polar system is envisaged for the Mark 3 simulator. The conversion from the Cartesian to the polar system is discussed in para 3.4.

3.2 Orientation of the Target Course

In addition to the relative positions of target and missile it is also necessary to simulate the orientation of the target course with respect to the line taken as the z axis, and the given data will in general include the following items:

(a) The velocity U, of the target (which is assumed at present to be flying a straight and level course).

(b) The missile velocity, V.

(c) Two of the following three angles (see Fig. 1):

β = the course angle, i.e. the angle between the target course and the projection of the central trajectory in the plane of the wings (Angle TOQ in Fig. 1),

θ = angle between the central trajectory and its projection in the plane of the wings (Angle QOC in Fig. 1),

η = angle between the central trajectory and the target course (Angle TOC in Fig. 1).

Any two of these angles together define the direction of the central trajectory, and are connected by the following equation:

$$\cos\beta\cos\theta = \cos\eta.$$

From the above data it is possible to calculate the magnitude, V_R, of the relative velocity of missile and target, and its direction, defined by angles B, A, C, corresponding to β, θ and η respectively (see Fig. 2). The line through the target centre, parallel to the relative velocity, is subsequently referred to as the V_R line.

Using a rectangular Cartesian system of coordinates O(a, b, c) with origin O at the target centre, Oa along the target course and Oc perpendicular to the plane of the wings (see Fig. 3), with unit vectors $\underline{i}$, $\underline{j}$ and $\underline{k}$ along Oa, Ob and Oc respectively:

Target velocity $= U\underline{i}$,

missile velocity $= -V\cos\theta\cos\beta\,\underline{i} - V\cos\theta\sin\beta\,\underline{j} + V\sin\theta\,\underline{k}$,

therefore relative velocity $= -(U+V\cos\theta)\cos\beta)\,\underline{i} - V\cos\theta\sin\beta\,\underline{j} + V\sin\theta\,\underline{k}$,

also, relative velocity $= -V_R\cos A\cos B\,\underline{i} - V_R\cos A\sin B\,\underline{j} + V_R\sin A\,\underline{k}$,

so that V_R $= (U^2 + V^2 + 2UV\cos\beta\cos\theta)^{\frac{1}{2}}$ .... (1)

Again, equating vector coefficients in the two expressions for relative velocity, we see that

$$V_R\cos A\cos B = U + V\cos\theta\cos\beta,$$

$$V_R\cos A\sin B = V\cos\theta\sin\beta,$$

and $V_R\sin A = V\sin\theta.$

Thus, $\sin A = \dfrac{V\sin\theta}{V_R} = \dfrac{V\sin\theta}{(U^2 + V^2 + 2UV\cos\beta\cos\theta)^{\frac{1}{2}}}$, ... (2)

and $\tan B = \dfrac{V\cos\theta\sin\beta}{U + V\cos\theta\cos\beta}$, ... (3)

while from Fig. 2 we note that $\cos C = \cos A\cos B$.

It is also necessary to know the angle γ between the V_R line and the central trajectory. From the triangle of velocities in the common velocity plane we see that this is given by the equation

$$\sin\gamma = \frac{U\sin\eta}{V_R}.$$

4. The Optical Head and its Use

It is the purpose of the optical head to simulate the projection of fragments from a bursting projectile. The construction of the head in the Marks 1 and 2 simulators is similar in principle, but that in the Mark 3 is radically different. The basic theory given below applies, however, to all models.

4.1 Fragmentation

The majority of the fragments from an exploding missile are projected at high velocity within the space contained by the surfaces of two cones, whose common axis is the axis of the missile. They may be considered as emanating from a point source at the centre of the missile, the semi-angles of the cones being defined as the beam limits (θ_1 and θ_2 in Fig. 4). The values of these beam limits depend on the magnitudes and directions of the initial fragment velocities V_o (with respect to the missile), and the missile remaining velocity at the instant of detonation (V). Two types of fragment beam may be considered:

(a) with the missile at rest, the fragments are projected with velocity V_o (which varies along the length of the missile) relative to it. Because of the internal taper of the cavity of the missile, and the fact that the missile is of finite length, the fragments are distributed in a beam about the plane through the missile centre and perpendicular to its axis. This is known as the "Static Beam".

(b) When the missile is moving at remaining velocity V, the fragments are projected with velocity V_F (where $V_F = V_o + V$) relative to fixed space. This directs the beam forward by an amount which depends on the variation of V_o along the missile. Thus the beam is not necessarily of the same width as when the missile is at rest, θ_1 and θ_2 both being smaller. This is known as the 'Dynamic Beam' and Fig. 4 is an illustration of a section through it.

The missile may be designed to give fragments of one or other of two types:

(a) Fragments from a 'naturally' fragmenting missile or shell, which vary in shape and mass over a considerable range. The mass distribution may be determined approximately from the equation:

$$P_i = \exp(-m_i^{\frac{1}{2}}/M_o),$$

where P_i = the proportion of the total number of fragments of mass $> m_i$,

M_o = the 'fragmentation parameter', which is determined by the missile geometry, the steel and explosive of the missile (Ref. 5). The fragments vary in velocity and density of distribution across the beam.

(b) 'Controlled' fragments, which are of uniform mass and shape, and normally are more uniformly distributed across the beam. The fragment velocity varies along the missile length but these variations are not usually large.

All considerations of the number or type of fragments are left to a late stage of the calculations, and the optical head is concerned only with simulation of the direction of throw of the fragments.

4.2 Target Motion

In the time during which the fragment travels to the target, the target moves along its course. The distance it moves is a function of its velocity (U), the fragment velocity (V_F), and the relative positions of the target and missile at the moment the latter is detonated. A complication arises because the fragment velocity is not constant, since the fragment suffers retardation due to air resistance.

Fig. 4 may be modified to allow for this by another vectorial addition to the fragment velocities, which must vary as the distance from the missile increases. The result is the curved beam of the type shown in Fig. 6 for a target passing directly overhead. The graphical problem is more complicated if the missile course and target course are skew lines; the beam is not symmetrical about any standard reference line.

The effect of target motion during fragment flight may be represented by one of three methods:

(a) by setting the distorted fragment beam (Fig. 6) on the optical head. It is of course not possible to simulate the curved limits of this beam and the variation of the fragment velocity with distance due to retardation in air must be neglected. The fragment velocity chosen can however, be taken as a mean value consistent with some point along the fragment path. The point chosen depends upon the conditions of the engagement which is being considered, and the shot distribution is a relevant factor. The variation of fragment initial velocity over the length of the missile also complicates the choice but as a general rule, the velocity chosen should be a weighted mean taking into account the number of effective fragments from each of many sections of the missile available at the chosen distance from the point of burst.

(b) by setting the dynamic beam on the optical head. Target motion is then taken into account by moving the model aircraft along its axis by an amount which is determined by successive approximations, and which varies with each component considered.

(c) by setting the static beam on the optical head and moving the model target by an appropriate amount in the direction of the relative velocity of missile and target.

In practice the second of these methods has been found to be the most convenient and has been generally adopted, even though a small error arises due to the fact that the direction along which the solid angle is measured is the actual direction of flight of the fragment rather than the direction relative to the target.

The first method has been rejected because of the approximation involved in the estimation of a mean fragment velocity and because of the complicated nature of the design of an optical head to give the distorted fragment beam. The third method is undesirable owing to the large distances at model scale through which it would be necessary to move the target.

It is emphasised at this stage that, whichever method be used, target travel must be allowed for before the record of those components illuminated by the light beam is taken and their distances from the point of burst are measured.

5. Solid Angle Measurements

The physical concept of the area presented to the fragments of a beam by the vulnerable components of an aircraft is complicated by the fact that the fragments emanate from the burst point in many directions, and there is no unique plane perpendicular to all directions of fragment projection. For this reason the use of solid angle is preferred to that of presented area.

The part of a vulnerable component which lies within the beam of fragments is indicated by the part of the component in the model target which is illuminated by the light beam, when the target is in the position reached when the component is struck. The ratio between the solid angle subtended by the illuminated area and the solid angle contained by the complete beam gives the proportion of the total number of fragments which may be expected to hit the component under consideration, assuming the fragment density to be uniform over the beam width.

In the Mark 1 and Mark 2 simulators the solid angle subtended by the illuminated parts of the target is assessed by measurement of the area

of shadow cast by the target on a screen or set of screens. These screens which are plane in the Mark 1 model and hemispherical in the Mark 2 are calibrated in convenient units of solid angle, the total solid angle concerned being measured by counting the number of units which are covered by the shadow.

Assessment of solid angle is automatic in the Mark 3 simulator and is achieved by projecting a beam of light to cover each of a number of small areas of the surface of a sphere in turn, each area representing a unit of solid angle. A counting device records the number of cases in which the target model obstructs and reflects the light beam and this record is then converted into a solid angle reading.

6. The Use of the Data from the Simulator

The data obtained from the simulator consist of the knowledge of which components are sprayed by the fragment beam, the distances of these components from the burst point when they are hit and the solid angle subtended by them at the point of burst. The remainder of the calculation of the lethality of a weapon is a theoretical operation.

From a knowledge of the mass, initial velocity and retardation of the fragment and the vulnerability of the component, graphs can be prepared to show the number of fragments from a missile effective against a component, plotted against distance.

The term 'number of effective fragments' is defined as the product of the number of fragments from the missile and the probability that a hit by any one of those fragments will cause damage of the required kind.

If $n(d)$ be the number of fragments effective in damaging a component at distance d, and if these fragments be distributed uniformly over the fragment beam, then the probability of at least one effective hit on the component is given by

$$p = 1-\exp\left\{\frac{-n(d)\omega}{\Omega}\right\},$$

where ω is the solid angle subtended at the point of burst by the part of the component within the fragment beam, and Ω is the total solid angle over which all the fragments are spread. It is assumed that ω/Ω is small and that $n(d)\omega/\Omega$ remains finite.

By this method, it is possible to calculate the probability of damaging a component of the target for any point of burst (x, y, z), this probability being zero if the component is wholly outside the beam of fragments.

The probability of defeating a singly vulnerable aircraft from a burst at (x, y, z) can be obtained by considering the survival probabilities of each of the components and may be written

$$p(x, y, z) = 1 - (1-p_1)(1-p_2) \;\; \ldots\ldots. \;\; (1-p_m)$$

where $p_1, p_2 \;\ldots.\; p_m$ are the kill probabilities on the m components from a burst at this point.

The probability (P) that the aircraft is defeated by a single shot is given by

$$P = \iiint_{\substack{\text{all}\\\text{space}}} p_f p_b p_l \; dx\, dy\, dz ,$$

where p_f is the probability distribution of fire control errors which determines the probability that the projectile passes through the element dx dy dz.

p_b is the probability that a missile in the element of space dx dy dz should burst there, and depends on the fuze burst pattern.

p_1 is the probability of defeating the aircraft from a burst in dx dy dz, computed from the simulator data.

It should be noted that, in computing the probability of defeating a target by a single shot, the function p_1 in the above triple integral must represent the probability that the aircraft as a whole is defeated by a burst in the element dx dy dz. For a multiply vulnerable aircraft this function must take account of the numbers of components in each of the sets of components which must be damaged in order to defeat the target, and of a summation, similar to that above, over the various classes of components in the aircraft.

The calculation of the probability of defeating the target with a series of shots is more complicated, and involves the accumulation of damage to members of the classes of components during the engagement. An example of such a calculation, involving the use of the Mark 1 simulator, is given in Reference 6.

APPENDIX A.

Description of the Mark 1 Simulator

1. This simulator is at present in operation at the A.D.E. Fort Halstead. A diagrammatic sketch is given in Fig. 7. It employs a Cartesian system of coordinates, the x and z axes being horizontal and the y axis vertical. The simulator is arranged so that the optical head moves in the direction of the y axis only, while the target assembly moves in the x and z directions

Fig. 8 shows the details of the optical head originally planned for this simulator. The light source, at B, is as near a point source as can be obtained commercially. The light is confined to a conical beam by the edges of a disc and cylinder, as shown in the figure, and this beam is initially symmetrical about their common axis. The disc and cylinder are fixed relative to the light source in the x and y directions and move in the z direction, governing in this movement the beam limits, θ_1 and θ_2 which are set directly from a graduated scale. The light assembly is pivoted about an axis BB' through the source parallel to the x axis. This movement is to allow for the setting of the angle between the missile course and the z axis, and its magnitude (ξ) depends on the line that this axis represents: e.g. if the z axis represents the relative velocity line, then $\xi = \gamma$. The assembly is rotatable about the axis (zz') in order to bring the setting ξ into the common velocity plane.

An additional setting is necessary if the distorted fragment beam (allowing for target travel) is required, this being a movement of the light source within its housing in the common velocity plane parallel to the target course. To simplify construction, provision for this last setting and for rotation about the axis BB' was not made in the optical head finally produced. For angle-off attacks this leads to the choice of the central trajectory as z axis since, with this choice, allowance for target travel is most easily made. This omission will be made good in the Marks 2 and 3 simulators now being produced.

Two types of target are being used at present. They are:-

(a) A solid wooden model. This type is used in problems involving the structure of the aircraft.

(b) A skeleton model. This is a bare skeleton of the aircraft structure, made of wire, with the components fitted into it in solid form.

The target is moved along a guide rail parallel to its axis to allow target travel during fragment flight to be simulated. As this apparatus does not allow a close approach of the target to the light assembly, the rail is omitted wherever possible. When a head-on or tail-on attack is considered, the motion of the target is along the z axis, and may be allowed for by using the existing movement in this direction, or by setting up the optical head to simulate the <u>relative</u> fragment beam.

2. As a preliminary to the working of a problem the target must be set up in its correct position and orientation with respect to the optical head. The system for setting up can be followed on Fig. 7.

The target is mounted through its centre O on a vertical bar OM about which it is free to turn in a plane perpendicular to the bar. The bar is itself mounted on a right-angled arm MNP, in which MN is horizontal, and NP initially vertical, and the arm can be rotated about a horizontal axis PQ,

level with O. A second right-angled arm QRS (QR vertical and RS horizontal) supports the first, and the whole structure turns about a vertical axis ST directly below OM.

The point T can be moved along a horizontal bar parallel to the z axis, and variation of the x coordinate can be achieved by lateral movement of the bar itself in the x direction.

The y coordinate is fixed by vertical movement of the light source along a bar parallel to the y axis.

In the present set-up of the simulator, the arm QRS is fixed so that SR is parallel to the x axis and hence OPQ is the x axis. Only two of the possible three angular displacements of the target will therefore be allowed:

(i) rotation about OM i.e. about the y axis, to adjust angle B if the V_R line is chosen as the z axis or β if the central trajectory is chosen.

(ii) rotation about OPQ i.e. about the x axis, to adjust angle A if the V_R line is chosen as the x axis or θ if the central trajectory is chosen.

The target is in the zero position when the x and z readings on their respective scales are zero and the target is horizontal and pointing in the positive z direction i.e. towards the light source.

Three possible types of engagement will be considered separately:

(i) Head-on attack.

(ii) Direct approacher.

(iii) Crossing target.

The methods for setting up the target will be considered separately and described in detail for the case in which the V_R line is chosen as the z axis. If the central trajectory is chosen as the z axis the procedure is similar - the only variations being the magnitudes of the angular rotations.

(a) <u>Head-on attack</u>

In this type of engagement the relative velocity line is also the central trajectory and in line with the target course. Hence the angles A, B and C are all zero and the only variable parameters are the coordinates (x, y, z) of the burst position.

The coordinates x and z are fixed by movement of the base point T a corresponding distance from the zero position in each direction. The movements take place in the negative x and z directions as it is the target, and hence the origin, which is being moved.

Movement of the light source an appropriate distance y in the positive direction adjusts the third coordinate. The light source then has coordinates x, y, z relative to the target centre.

(b) <u>Direct approacher</u>

For the direct approaching target the coordinates x, y and z are fixed as in the case of head-on attack considered above.

The central trajectory and the target course - and consequently the relative velocity line are in the same vertical plane (the common velocity plane) and hence the angles β and B are both zero, while $\theta = \eta$ and $A = C$.

The final set-up is achieved by turning the target from the zero position through an angle A about the axis PQ.

(c) Crossing target

The positions of the target centre and the light source are again fixed as described above. The orientation of the target course is achieved by turning the target from the zero position through an angle A about the axis PQ and angle B about the axis OM where A and B are given by equations 2 and 3 in para. 3.2.

3. In practice the given data will not always include the rectangular Cartesian coordinates x, y, z of the burst position explicitly, and it may be necessary to derive these parameters from those of another coordinate system. The system most likely to be used is defined by ϕ r, z or ϕ, R, z where

ϕ = angle between the common velocity plane* and the plane containing the V_R line and the burst point (subsequently referred to as the ϕ plane)

r = perpendicular distance from the burst point to the V_R line

R = distance between the target centre and the burst point, at the instant of burst

z is the usual Cartesian coordinate and $r^2 + z^2 = R^2$.

If ψ is defined as the angle between the yz plane and the common velocity plane then the angle between the yz plane and the ϕ plane is $\psi \pm \phi$, the sign being positive if ψ and ϕ are both measured from the yz plane in the same direction. (The case of head-on attack is considered separately later in the text).

The Cartesian coordinates of the point ϕ, r, z are therefore given by the following equations:

$$x = r \sin(\psi + \phi),$$

$$y = r \cos(\psi + \phi),$$

$$z = z.$$

In order to solve the above equations it is first necessary to calculate ψ. Now the magnitudes of the components of the target velocity along the x, y and z axes respectively are:-

$$U \sin C \sin \psi,$$

$$U \sin C \cos \psi,$$

and $$U \cos C.$$

From Fig. 2 we see that these magnitudes may be written respectively as:-

$$U \sin B,$$

$$U \cos B \sin A,$$

and $$U \cos B \cos A,$$

so that $$U \sin C \sin \psi = U \sin B,$$

* Common velocity plane: plane containing the target course, central trajectory and V_R line.

and $U \sin C \cos \psi = U \cos B \sin A;$

therefore $\tan \psi = \dfrac{\tan B}{\sin A}$

4. The target and light assemblies having been set up in their relative positions by movements along the x, y and z axes, and the target rotated into the correct orientation, the 'dynamic beam' limits are set on the optical head. The light head is then rotated about BB' by the angle ξ (assuming that this movement be possible) and then about the axis parallel to the z axis to bring the former movement into the common velocity plane (i.e. through the angle ψ, assuming BB' initially parallel to the x axis). The positions and orientations of the light head and target now represent the exact engagement conditions at the instant of burst.

To allow for target travel a method of successive approximation is used. The distances travelled by the target and fragment are in the ratio of their velocities, (U/V_F). V_F is a function of distance but the ratio U/V_F may be previously determined as a function of distance of fragment travel. From a suitable graph the corresponding target travel is obtainable for any given distance of fragment travel. The method is as follows:

(a) Measure the distance between the light source and the component at the instant of burst (with a pair of calipers). This is taken as a first approximation to the fragment travel, and the corresponding target travel is obtained from the graph.

(b) The target is moved along its course by this amount.

(c) Measure the distance between the light source and the new position of the component and obtain the corresponding target travel.

(d) The target position is adjusted so that its distance from the original position is the new target travel distance.

(e) This procedure is repeated until the adjustment of the target position necessary is less than six inches full scale. This should not require more than two settings, unless the target velocity is very great.

At this point it is possible to determine whether the component is struck by fragments and to measure its distance from the point of burst. This process is repeated for all vulnerable components likely to be struck and the information recorded in an appropriate table. In the case of large components, it may be necessary to record a range of distances corresponding to elements of the component.

5. Measurement of solid angle is achieved on three screens, A, B and C perpendicular to the x, y and z axes respectively. Charts are attached to the A and C screens, calibrated in a series of small areas each subtending the same unit of solid angle at the light source. Movement of the light source takes place in the y direction only (i.e. parallel to these two screens) and for every displacement of the light source, the charts are moved up or down the screens correspondingly.

Calibration of the B screen was not practicable since the perpendicular distance between the light source and this screen is variable, and the sizes and shapes of the areas subtending units of solid angle at the light source are therefore also variable. It was consequently necessary to calculate separately the solid angle subtended by the portion of the shadow which falls on the B screen, and a method for doing so is described below.

5.1 Calibration of the charts for the A and C screens

The calibration of the charts depends upon the orientation of the axis of the beam relative to the screens and the distances between the screens and the light source, and is most easily achieved by first calibrating a screen which is perpendicular to the axis of the cones and then projecting this grid into a screen with the specified orientation and at the desired distance.

The fragments from a fragmenting missile are projected within the region between two cones of semi-angles θ_1 and θ_2 with common axis along the axis of the missile (see Fig. 4). θ_1 and θ_2 are defined as the beam limits and $\theta_2 - \theta_1$ as the width of the fragment beam.

If the beam of light representing the fragment beam is thrown on to a screen which is perpendicular to the axis of the cones, and at a distance K from the light source, the illuminated area consists of the region between two circles of radii $K \tan \theta_1$ and $K \tan \theta_2$, and with common centre on the axis of the cones. For a chosen value of K, concentric circles are drawn with radii $K \tan \theta$ for values of θ at $2\frac{1}{2}^{\circ}$ intervals between 0 and the highest θ value permitted by the dimensions of the screen, thus indicating the boundaries of the areas on the screen which are illuminated by beams of various widths. The solid angle subtended at the light source by the area between two circles defined by θ_r and θ_{r+1} is given by $2\pi(\cos \theta_r - \cos \theta_{r+1})$ where $\theta_r < \theta_{r+1} < \pi$.

This expression is evaluated for each pair of adjacent circles, and the area divided into convenient units of solid angle by sets of radii.

The calibration of any other screen can then be achieved by projecting the above grid from the light source into the required plane; a family of conic sections corresponding to the circles and a set of concurrent straight lines taking the place of the radii. Each chart must be moved up and down its screen in sympathy with the movement of the light source, so that the point which is the projection of the centre of the circles is always on the axis of the light cones.

5.2 B screen Calculations

The calculations required in estimating the value of the solid angle subtended at the light source by the shadow on the B screen involves a great deal of computation, and it has been found desirable to formulate a method of approximation for obtaining these values. Such a method necessarily depends upon the approximations which may be made under the conditions of the particular engagement problem in question and although the method described below has been used so far, it may need to be adapted in future work.

The outline of the shadow is sketched on paper, on which are also marked beam angles at $2\frac{1}{2}^{\circ}$ intervals as on the calibrated charts, and the areas of shadow between adjacent beam angles are measured.

If l_i is the distance between the light source and the centre of the shadow in the i^{th} $2\frac{1}{2}^{\circ}$ zone between adjacent beam angles, and d is the perpendicular distance of the light source from the B screen, then the angle θ_i between the lines along which l_i and d are measured is given by

$$\cos \theta_i = d/l_i.$$

If the area of the shadow falling within the i^{th} zone be denoted by S_i then the solid angle subtended by S_i at the light source is approximately

$$\frac{S_i \cos \theta_i}{l_i^2} = \frac{S_i\, d}{l_i^2},$$

provided that S_i is small compared with l_i^2.

The measurements required from the simulator are therefore as follows

(i) The area of shadow in each angular zone,

(ii) The distances of the light source from the centre of the shadow in each angular zone,

(iii) The distance of the light source from the B screen.

The appropriate groups of the solid angles derived as above are then added to give the total solid angle subtended by the relevant parts of the target which are illuminated by the beam widths under consideration.

APPENDIX B

Description of the Mark 2 Simulator

1. The Mark 2 simulator can be regarded as a re-design of the Mark 1. Its construction was undertaken by the Mollart Engineering Co. Ltd., Surbiton, and should be complete by the end of 1953.

Several changes in detail have been made from the Mark 1 simulator, among which are:-

(a) The Cartesian coordinate system, previously chosen for defining the relative position of the target and the burst position of the projectile, is discarded in favour of the cylindrical polar system defined in paragraph 3.1 of the main text. This step has been taken to standardise coordinate systems with the V.T. fuse burst pattern model scale apparatus within the Armament Design Establishment, so that burst pattern data can be transferred directly to the simulator. The cylindrical polar system will also allow successive setting of many different burst positions with the minimum of effort. Using this system it has been possible to substitute one rotational for one translational setting, with a consequent reduction in weight and space.

(b) The z axis of the simulator is vertical and movement in r is horizontal. No long cantilever suspension of the target is therefore necessary and the consequent loss of accuracy is avoided.

(c) Three angular rotations of the target are possible in the Mark 1 apparatus, the two most convenient being used in any given problem. If, however, one angular setting of the target model is made in the common velocity plane then only one other setting need be used to give the correct target orientation. This latter combination is the one adopted for the Mark 2 simulator.

The derivation of these two settings from any method of specifying the target orientation is a simple calculation.

(d) Measurement of solid angle is obtained by counting the number of relevant units covered by the shadow of the component concerned on a portion of graduated glass sphere, centre the light source.

2. A general arrangement of the simulator is shown in Fig. 9. The light source A, which is secured to a concrete pier B, is similar in principle to that originally designed for the Mark 1 simulator. It can rotate about a vertical axis. The axis of the light source may be turned from the vertical through the angle γ in order to allow the setting of the angle between the missile axis and the relative velocity line (in cases where the relative velocity line is chosen on the z axis) γ may take all values up to 30^{o}. Rotation of the light source is power operated by means of the selsyn motor C which is run from a transmitter D, with manual control.

The whole target assembly moves in the r coordinate direction along horizontal bars E, the movement being controlled by the handle F. The z motion is controlled by the handle G, and vernier scales are provided for this and all other readings. The coordinate ϕ is adjusted by the sympathetic rotation of the optical head and the target assembly about vertical axes, the selsyn motor on the target assembly being at H.

The target aircraft fits over the tube K, and two rotations, one about the tube and the other through the bush L, provide the means of setting the target orientation. Target travel is measured along the tube K.

A glass quarter sphere is rotated about a horizontal diameter through the light source in such a way that three quarters of the complete sphere can be represented. This quarter sphere is calibrated in units of 0.001 steradians, and the solid angle subtended by any part of the target aircraft is assessed by counting the number of such units covered by the shadow cast.

3. It will be appreciated that the operation of the Mark 2 simulator is similar to that of the Mark 1, and the differences mentioned in para 1 of this Appendix have little effect on the general scheme of working.

The apparatus is operated by first setting the deviation γ of the axis of the optical head from the x axis, and rotating the head about the vertical axis to ensure that this setting is made in the vertical plane containing the light source and the target centre. The target direction of flight is then set in this plane and the selsyn motors activated to obtain sympathetic rotation of the optical head and the target assembly about their respective vertical axes.

The orientation of the target course with respect to the x axis, assuming the latter to be the direction of relative velocity of missile and target, can be obtained by:

(a) rotation of the aircraft on the tube K through the angle δ, where δ is defined by

$$\cot \delta = \tan \theta / \sin \beta$$

(b) rotation of the assembly through the bush L through the angle $(\eta - \gamma)$.

These rotations should be made in the above order; it should be understood that the zero position of the plane of the wings of the target, from which the setting δ is made, is vertical and perpendicular to the plane containing the light source and the target centre.

The polar coordinates of the point of burst with respect to the target centre can then be set on the simulator.

4. Certain characteristics of the apparatus should be mentioned, which (before any operating experience has been gained) do not appear to limit the use of the simulator unduly:

(a) due to the position of the quarter sphere, a value of r greater than 200 ft. at 1/72 scale cannot be obtained: this is unlikely to be a serious limitation.

(b) values of z up to 36 ft. below, and 144 ft. above, the light source can be obtained at 1/72 scale: this is likely to be sufficient. Both this range and that in (a) above can be extended by change of scale.

(c) there are some regions with r less than about 30 ft. in which the light head obstructs the target support. This is likely to affect at all seriously only those problems involving projection of fragments within a cone of semi-angle 20° forward from the missile. Such regions can be adequately represented on the Mark 1 simulator and, it is hoped, eventually on the Mark 3.

(d) the range of the angles θ_1 and θ_2 is 0 to 135° measured from the forward axis of the optical head: some small amount of obscuration is caused by supports for the forward disc which is removable.

(e) the limit of target travel is 60 ft. full scale - this is likely to be adequate.

APPENDIX C

Description of the Mark 3 Simulator

At the same time as discussions took place regarding the construction of the Mark 2 simulator, a contract was placed with the General Electric Company at North Wembley to investigate methods of recording automatically the solid angle subtended by the components of the aircraft at the point of burst of the missile. The recording of solid angles in previous models was judged to take the major part of the operator time, and was therefore the measurement which it was most desirable to make automatic.

An apparatus has been suggested by the G.E.C. which in practice replaces the optical head and the sphere in the Mark 2 simulator and which has been assigned the name OSAC (optical solid angle counter). It is envisaged that the OSAC will be mounted in a manner similar to the optical head of the Mark 2 simulator and that the coordinate system, and the possible translations and orientations, will be identical with those of the Mark 2. To allow close approach, however, it is likely that the target assembly will be supported from above by a suitable framework.

The design of the OSAC has been confirmed as suitable by the A.D.E. and detailed design work is about to commence (July 1953). Delivery of one prototype is anticipated in June 1954, and the design of the necessary mechanical apparatus to provide the orientations and translations will be undertaken by the Mollart Engineering Company.

2. A block diagram of the design of the OSAC is shown in Fig. 10, and general arrangement drawings in Fig. 11. The apparatus projects a narrow parallel beam of light as from the centre (on a rotating mirror within the turret head), of an imaginary sphere, this centre representing the position of the exploding missile. The beam can scan the region of space which allows the angles θ_1 and θ_2 to have any values between 0 and 135°, measured from the upward vertical through the turret head. The apparatus is placed in the correct orientation and position with respect to the target, which is painted matt white. Reflection from the target when struck by the light beam operates a gate circuit (A in Fig. 10).

A small sphere (shown in the left hand drawing of Fig. 11) has been indented along a spiral path in such a way that the untouched surface between indentations is of constant area and therefore represents a convenient unit of solid angle. On to this sphere is directed a second beam of light and the reflections from each of the small areas of the surface of the sphere may be counted on an electronic counter. The sphere and the apparatus producing the counting signal may be rotated in such a way that reflections from all the small surface areas may be counted in succession, and the mirror in the turret head turns so that the original beam of light is always projected in the direction normal to the small area illuminated. This light beam, therefore passes through a unit of solid angle on the imaginary sphere corresponding to that illuminated on the small sphere.

As the counter is controlled by the gate A, counting takes place only when the original light beam strikes the target aircraft, and by this means the number of small surface areas for which the target is illuminated may be recorded. The solid angle subtended by the target follows by direct multiplication of this number and the unit of solid angle subtended by the small areas.

The scan of the imaginary sphere can be limited by a device which operates gate B in Fig. 10, and allows counting only within the chosen limits

θ_1 and θ_2. This device is shown as the programme disc assembly in Fig. 11, which also shows the centre of the imaginary sphere in the turret head.

In order to exclude stray light during operation, the simulator is likely to be enclosed in a light proof screen, fitted with suitable interlocks for switching general lighting inside. In order to alter any rotational or translational setting, this screen must be opened and it has been thought desirable to investigate remote control of the following movements:-

(a) the translations in the z and r directions,

(b) the rotation ϕ,

(c) the target travel along its course.

If remote control of these movements proves difficult or expensive, it may be desirable to limit it to the motion in the z direction, this being the most used. As the target travel varies with any change in r, ϕ or z, remote control of any one of the coordinates necessitates remote control of the target travel setting to make it worthwhile. There is no requirement for remote control of the setting of θ_1 and θ_2, as this is occasional only.

3. The setting up of the simulator with regard to the orientation of the OSAC and the target, and the polar coordinates of the position of burst of the missile, are envisaged as being exactly as for the Mark 2 simulator. The likely method of operation is to make the setting of z last and to run through a series of positions of z keeping r, ϕ and the other settings fixed; the other coordinates could then be altered in turn and the procedure repeated.

For each point (r, ϕ, z) set on the simulator the solid angle subtended by a particular component at the point of burst of the missile can be assessed; individual components must be treated separately, owing to the inability of the OSAC to distinguish between them.

Since a zero solid angle indicates that the component is not struck by the fragments under the particular conditions concerned, the value of solid angle provides the greater part of the information stated as required in the Introduction to the main text. It remains to determine the distance of the burst from the components struck. This can be measured directly by means of calipers.

It has been suggested, however, that this distance can be calculated directly from the parameters defining the engagement, and that the OSAC should be regarded only as a device for obtaining values of solid angles which can be fed into a programme for an electronic computing machine. As the solid angle is the only quantity which does not lend itself to evaluation by this type of machine, it seems logical that the Mark 3 simulator should be used in conjunction with such a machine, and this method of use will be investigated.

4. The following characteristics of the Mark 3 simulator relating to the OSAC have been laid down:

(a) the closest approach to the apparent centre of the OSAC (the rotating mirror in the turret head) should represent 10 feet when the scale is 1/72.

(b) the limits of the setting of γ on the OSAC should be $\pm 30^\circ$.

(c) rotation of the OSAC about a vertical axis should be through 360° but it should not be continuously rotatable. This was laid down to avoid slip ring connections.

(d) the limits of setting of θ_1 and θ_2 should be 0 to 135° measured from the forward axis of the missile.

(e) the limits of inaccuracy of measurement of solid angle should be ± 1% on an area of 300 square feet at 200 feet full scale. This inaccuracy increases linearly with decrease of area at a given distance, and decreases as the square of decrease of distance for a given area.

(f) the cycle time for setting and scanning should not be more than one minute; faster speeds may be achieved in the final design.

References

1. B.R.L. Memo Report No. 495 - "A Method of Computing the Probability of Killing a Multiples Vulnerable Target with N rounds of fragmenting shell" - Herbert K. Weiss, September, 1949.

2. J.H.U. Report CM 641 - "The Survival Probability of a Multicomponent Airplane" - A. George Carlton, September, 1950.

3. Unofficial O.B. Statistics Group Publication - "A Method of Calculating Survival Chance in A.A. Engagements" - J. B. Parker.

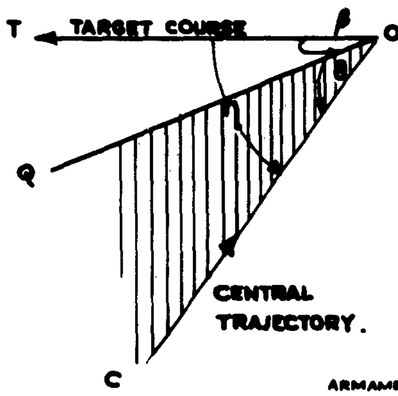
4. A.D.E. Report No. 11/53 "Assessments of the lethality of G.W. sub-projectile warheads against the TU4", - Audrey J. Boorer.

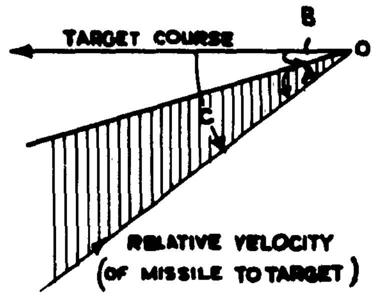
5. A.D.E. Report No. 8/48 - " A Theoretical Method of Estimating the Fragmentation Characteristics of a Projectile" Lt. Col. D. Tittensor.

6. C.T.2. Technical Note L 30 - "The Use of the A.A. engagement simulator in assessing Shell Lethality" - T. P. Turner, November, 1952.

FIGS. 1–3

DIAGRAMS SHOWING THE ANGLES USED TO DEFINE THE ORIENTATIONS OF THE CENTRAL TRAJECTORY AND THE RELATIVE VELOCITY LINE, RELATIVE TO THE TARGET COURSE.

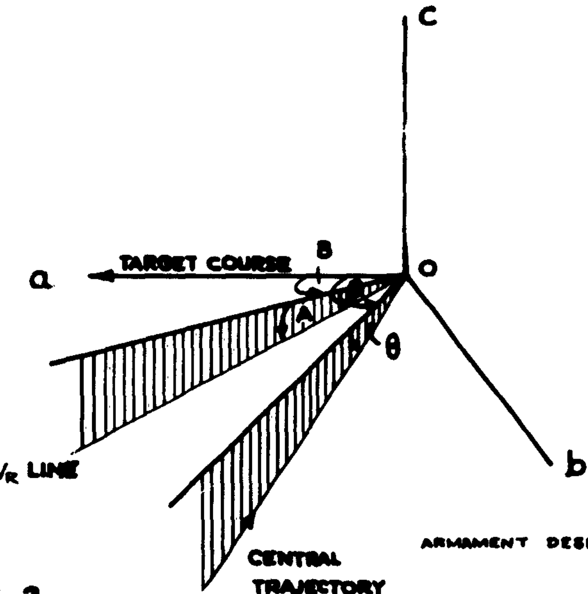




ARMAMENT DESIGN ESTST – M. OF S.

FIG. 1

FIG. 2

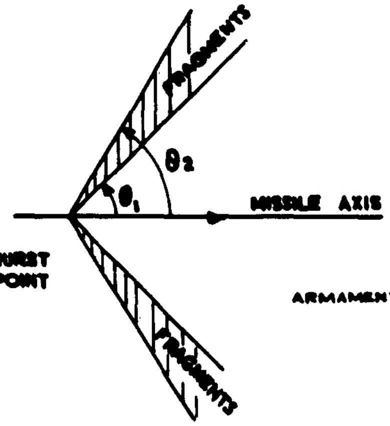


ARMAMENT DESIGN ESTST – M. OF S.

FIG. 3

VERTICAL PLANES ARE SHADED.
HEAVY LINES ARE IN HORIZONTAL PLANES.

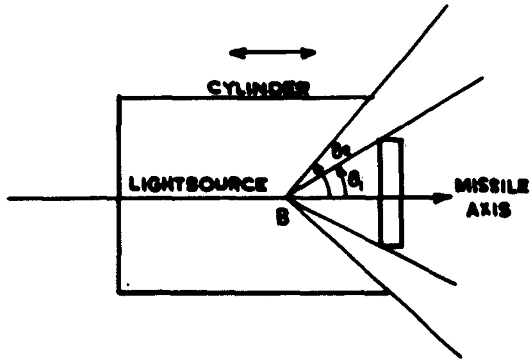
PLANE THROUGH FRAGMENT BEAM.



ARMAMENT DESIGN ESTB^T - M. OF S.

FIG. 4

SIMULATION OF FRAGMENT BEAM WIDTH.

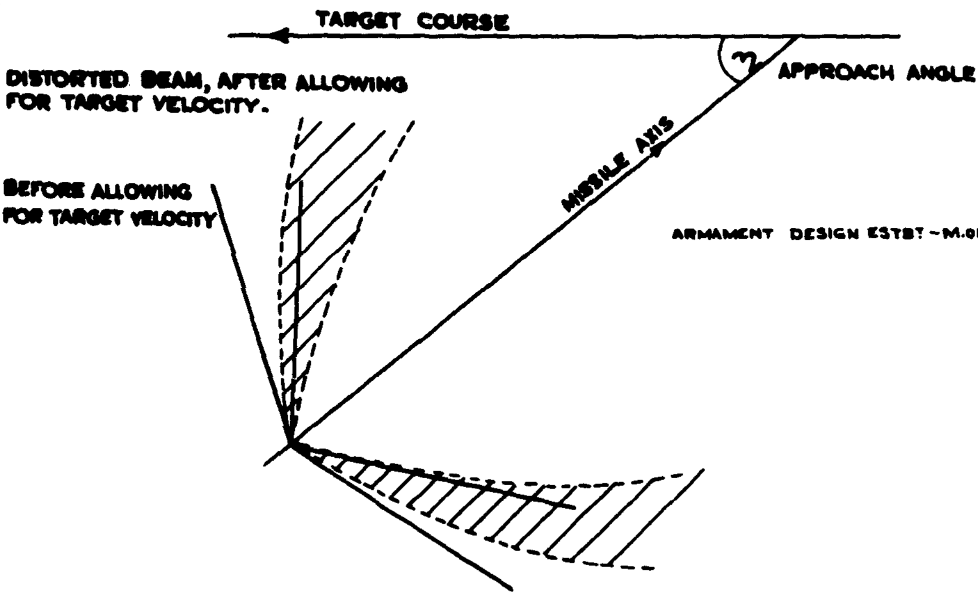


ARMAMENT DESIGN ESTB^T - M. OF S.

FIG. 5

FIG. 6

PLANE THROUGH FRAGMENT BEAM –
EFFECT OF TARGET VELOCITY

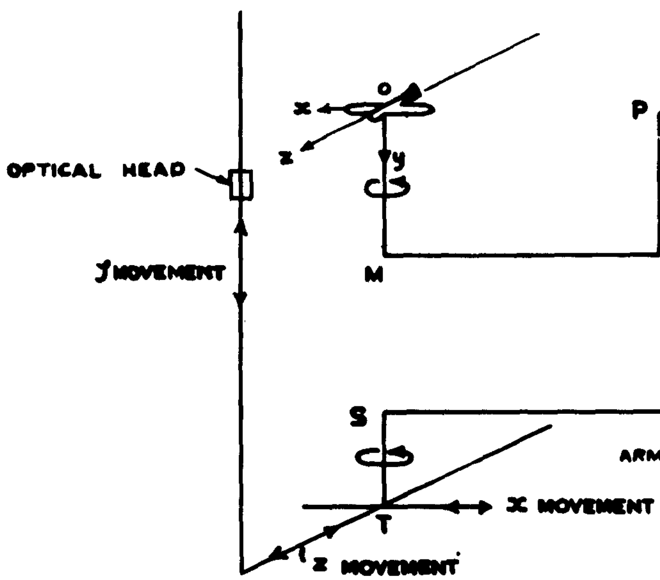


ARMAMENT DESIGN ESTBT – M. OF S.

FIG. 7

DIAGRAMMATIC SKETCH OF THE SYSTEM FOR SETTING UP THE RELATIVE POSITIONS AND ORIENTATIONS OF TARGET AND MISSILE (MK. I SIMULATOR)

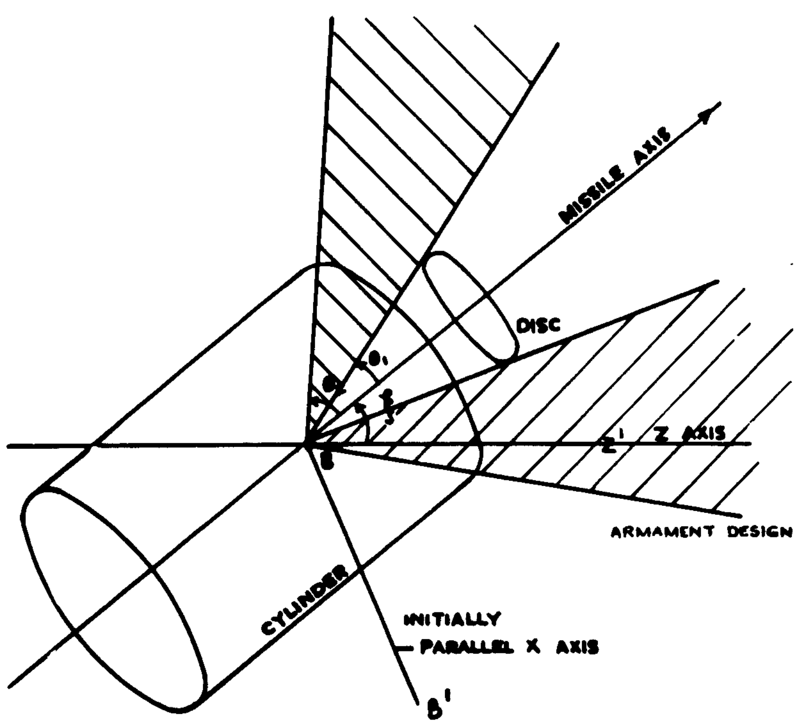
THE TARGET IS SHOWN IN THE ZERO POSITION.



ARMAMENT DESIGN ESTBT - M. OF S.

FIG. 8

OPTICAL HEAD.
Mk. I SIMULATOR.



ARMAMENT DESIGN ESTBT - M.OF S.

FIG. 9

GENERAL ARRANGEMENT OF MK. II SIMULATOR.

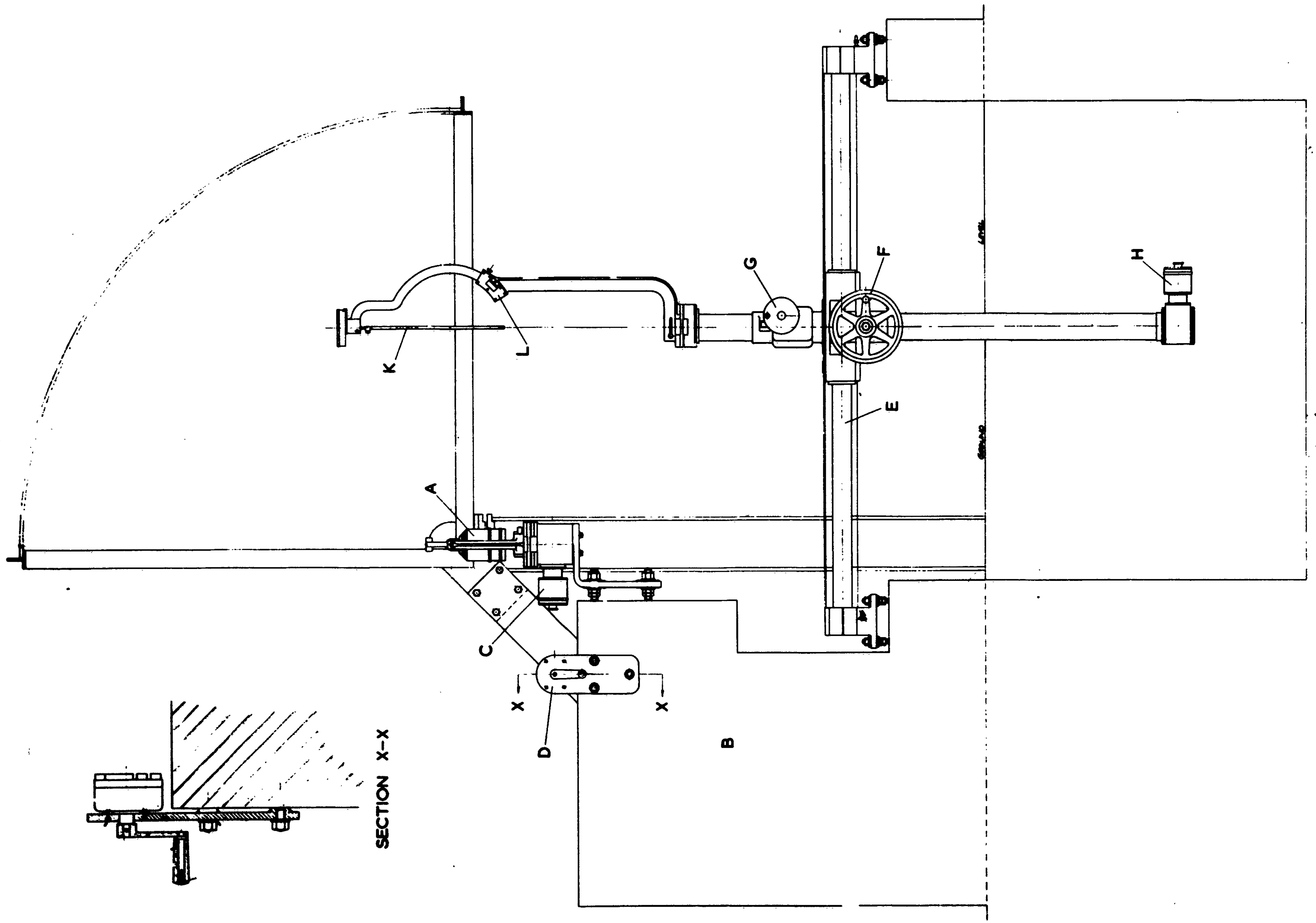


FIG. 10

SCHEMATIC BLOCK DIAGRAM OF OSAC (MK III SIMULATOR).

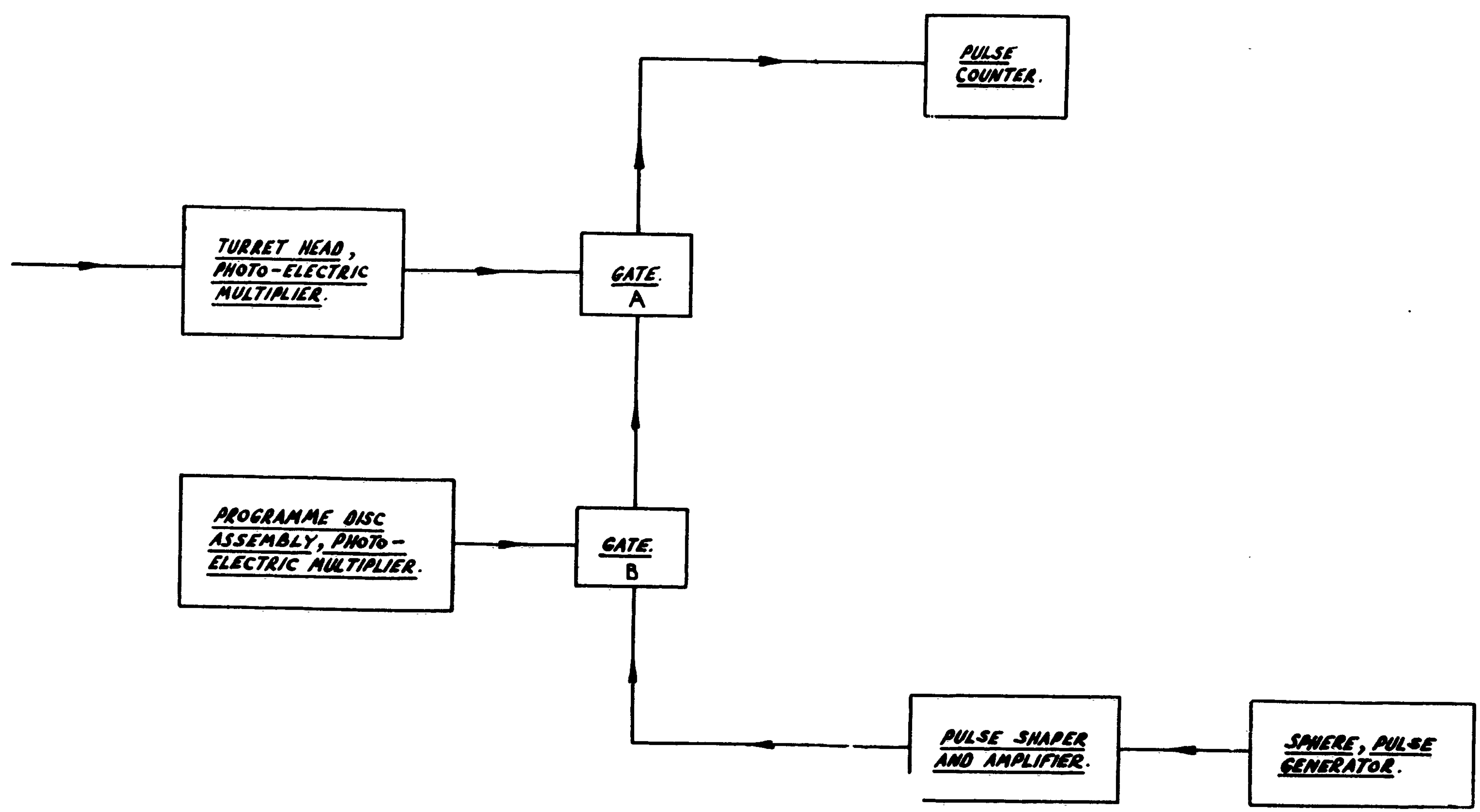
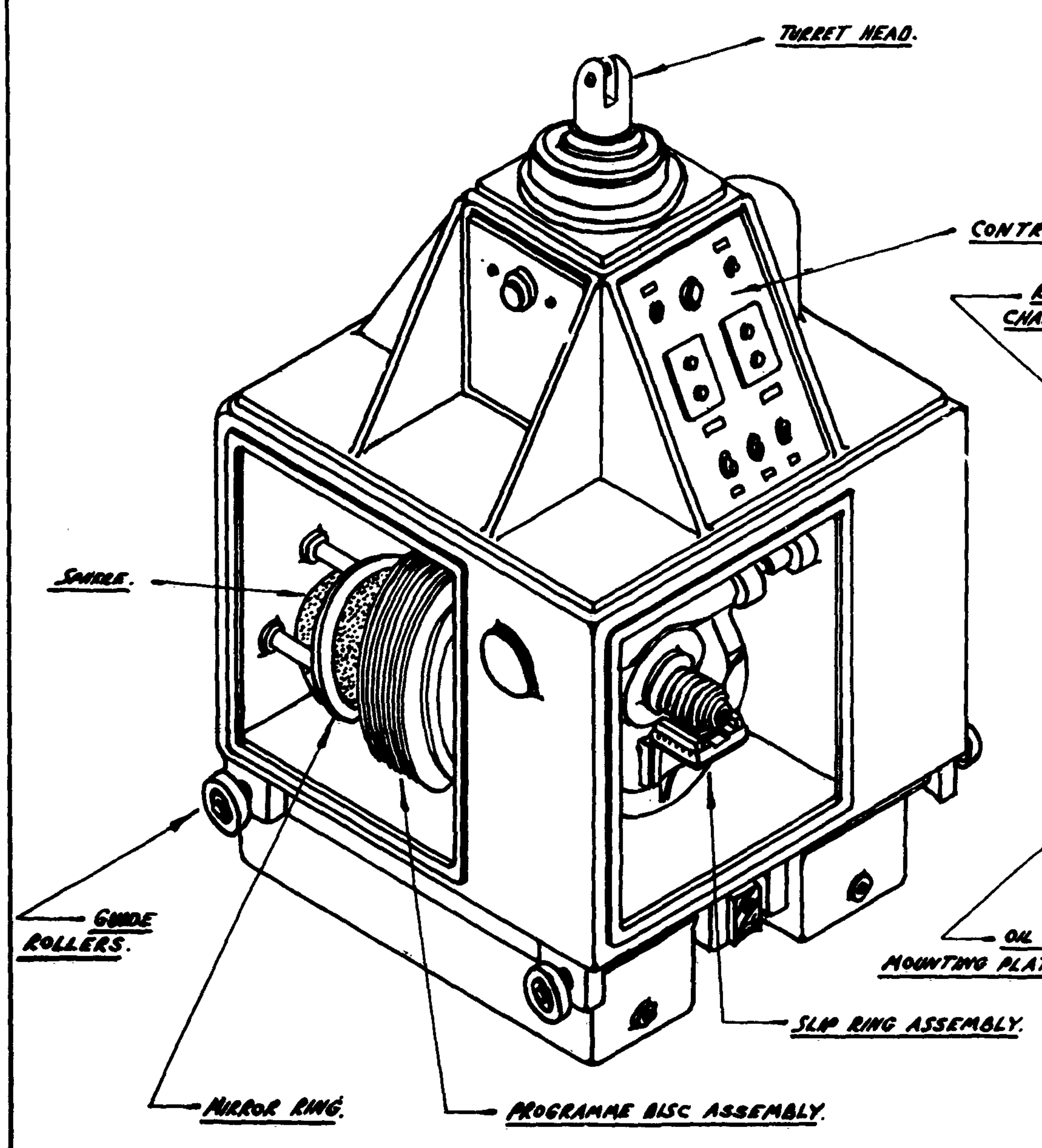
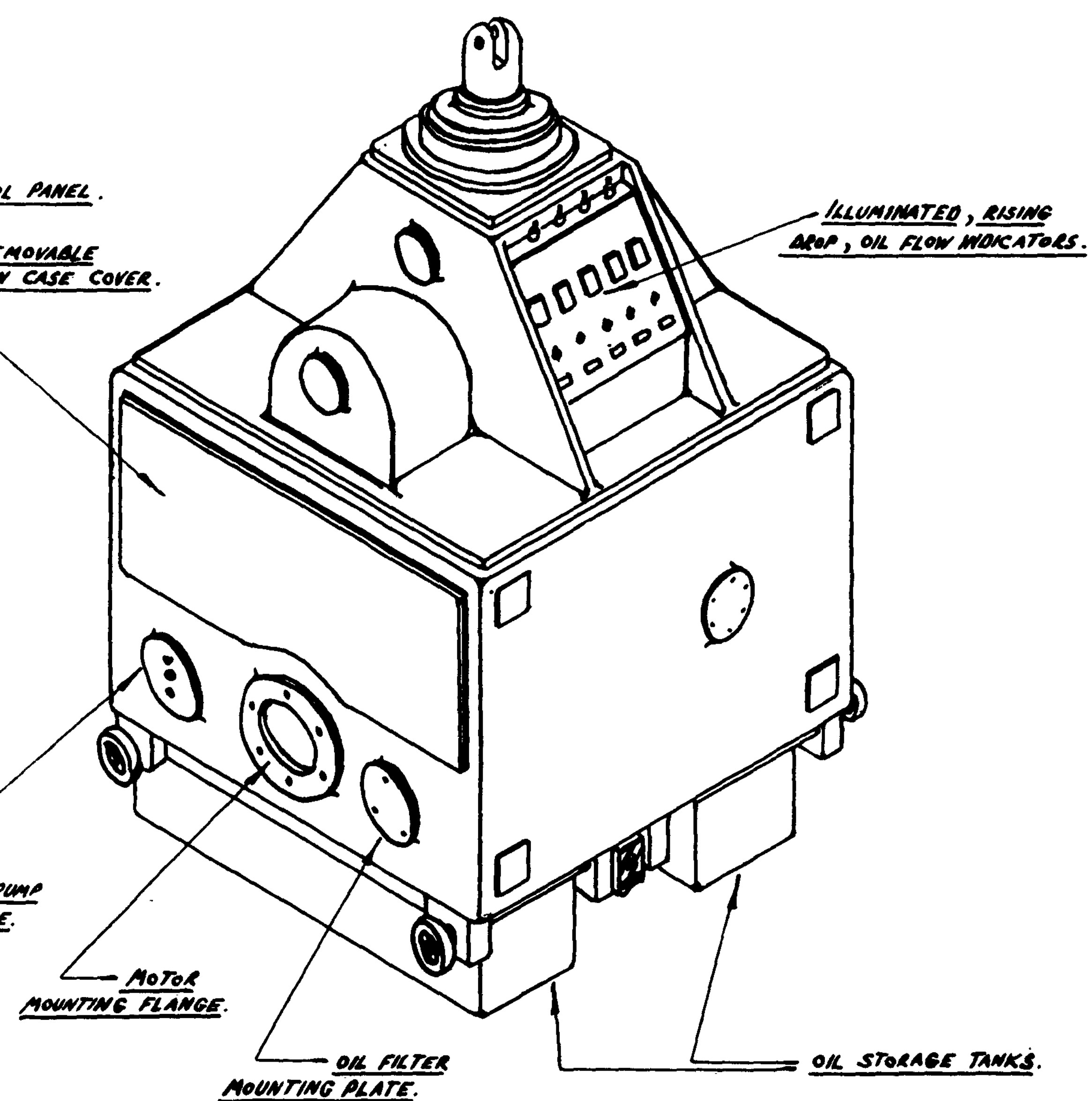


FIG. 11

GENERAL ARRANGEMENT SKETCHES OF OSAC (MK III SIMULATOR).



FRONT AND RIGHT HAND SIDE VIEW



REAR AND LEFT HAND SIDE VIEW

[dstl]

Information Centre
Knowledge Services
[dstl] *Porton Down,*
Salisbury
Wilts
SP4 0JQ
22060-6218
Tel: 01980-613753
Fax 01980-613970

Defense Technical Information Center (DTIC)
8725 John J. Kingman Road, Suit 0944
Fort Belvoir, VA 22060-6218
U.S.A.

AD#: AD029628

Date of Search: 1 August 2008

Record Summary: DEFE 15/340
Title: Development of an anti-aircraft engagement simulator
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
Former reference (Department) Technical Report No 9/53
Held by The National Archives, Kew

This document is now available at the National Archives, Kew, Surrey, United Kingdom.

DTIC has checked the National Archives Catalogue website (http://www.nationalarchives.gov.uk) and found the document is available and releasable to the public.

Access to UK public records is governed by statute, namely the Public Records Act, 1958, and the Public Records Act, 1967.
The document has been released under the 30 year rule.
(The vast majority of records selected for permanent preservation are made available to the public when they are 30 years old. This is commonly referred to as the 30 year rule and was established by the Public Records Act of 1967).

This document may be treated as UNLIMITED.